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Geodetic constraints on deformation rates and seismic hazard due to the San Felipe Shear Zone (Southern California)

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Abstract

We have studied surface deformation at the southern end of the San Jacinto fault using a combination of Interferometric Synthetic Aperture Radar (InSAR) and Global Positioning System (GPS) data. In particular, we processed and analyzed InSAR data from the ENVISAT satellite spanning a time period of 2003-2010. By combining data from the ascending and descending tracks we were able to isolate a horizontal (fault-parallel) velocity field. We also conducted several GPS campaign-style surveys of existing benchmarks to complement data from a continuous GPS sites. The data clearly show interseismic accumulation of strain in the San Felipe shear zone. This strain anomaly is asymmetric with respect to the Coyote Creek fault, which is believed to be the main branch of the San Jacinto fault south of the Santa Rosa mountains. The new data confirm our hypothesis that the Clark fault (the central segment of the San Jacinto fault) has a blind southern continuation into the Borrego badlands carrying slip rate as high as 10-12 mm/yr. If so, it may pose a significant seismic hazard.

Report

We investigated surface deformation in the San Felipe Shear Zone at the southern end of the San Jacinto fault (*Fialko, 2006; Janecke et al., 2010; Lindsey and Fialko, 2013*). The San Felipe Shear Zone is a continuation of the Clark segment of the San Jacinto fault (*Blisniuk et al., 2010; Sharp, 1967*); it extends from the southern tip of the Santa Rosa mountains for a few tens of kilometers to the South-East where it connects to the Superstition Hills/Elmore Ranch faults (Figure 1). It was identified based on a high gradient in the InSAR line-of-sight velocity that could not be readily attributed to interseismic deformation due to the sub-parallel Coyote Creek branch of the San Jacinto fault zone (*Fialko, 2006; Lindsey and Fialko, 2013*).

The Coyote Creek fault is currently believed to be the main branch of the San Jacinto fault (SJF) to the South of the Santa Rosa mountains (*Jennings, 1994*). We collected and analyzed new data to test the hypothesis that the San Felipe Shear Zone represents a “blind” continuation of the Clark fault in the sedimentary basin west of the Salton Sea (*Fialko, 2006; Janecke et al., 2010*). Such a possibility is suggested by the asymmetry in the surface strain rate with respect to the Coyote Creek fault (*Fialko, 2006*), robust microseismic activity following the strike of the Clark fault (Figures 1 and 2a), and active folding in the sedimentary cover (*Janecke et al., 2010*).

Another problem we addressed in this project relates to the presence and extent of shallow creep on the Coyote Creek fault. There are historic reports of triggered shallow creep on the Coyote Creek fault (e.g., *Louie et al., 1985*) that are used in the current UCERF estimates of seismic potential, but the long-term average rate and the along-strike and depth extent of shallow creep on the Coyote Creek fault are poorly constrained.

Building on results from our previous USGS-funded research (*Lindsey and Fialko, 2013; Manzo et al., 2012*), we analyzed data from two overlapping tracks (tracks 356 and 77) of the ENVISAT satellite covering the area of interest (Figure 1). One of the main limitations of InSAR measurements of interseismic deformation is a scalar nature of the radar range changes, that represent a projection of surface motion onto the satellite line of sight (e.g., *Bürgmann et al., 2000; Fialko et al., 2001; Rosen et al., 2000*). The line of sight (LOS) velocities from one look direction cannot be used to separate contributions from vertical and horizontal components of surface velocity. Indeed the InSAR data exhibit a much higher sensitivity to vertical motions of the ground compared to horizontal motions that are of primary interest in an area where tectonic deformation is accommodated primarily by strike-slip faults. For example, the LOS velocity field within the inferred San Felipe shear zone is affected by subsidence in the Ocotillo Wells area ($\sim 116^\circ\text{W}$, 33.1°N , Figure 1), presumably due to ground water pumping. In our prior analysis of LOS velocities we simply masked out areas of pronounced local subsidence (*Lindsey and Fialko, 2013*), assuming that elsewhere the LOS velocity field is dominated by horizontal motion.

This assumption generally holds, as evidenced by an overall agreement between the InSAR data and GPS data projected onto the satellite line-of-sight (*Fialko, 2006; Lundgren et al., 2009*). However, a close inspection of the available high-quality data reveals that in certain areas there are small but systematic differences between the InSAR and projected horizontal GPS velocities

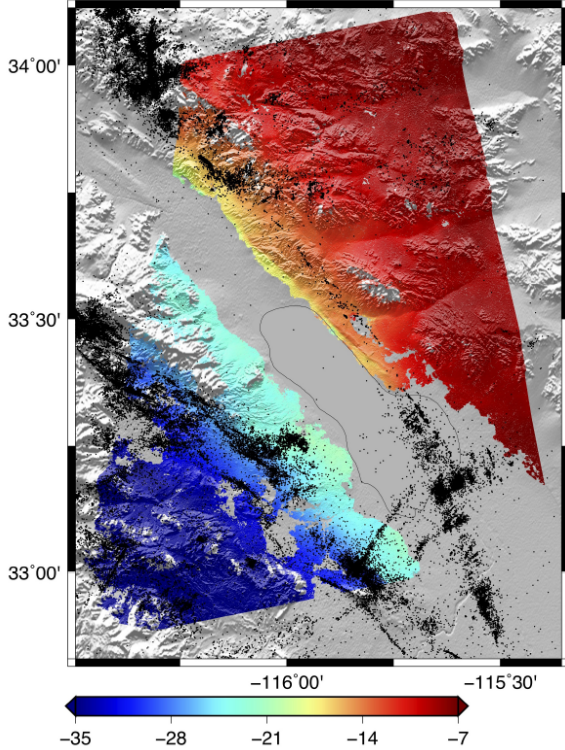


Figure 1: Fault-parallel horizontal velocity field in mm/yr (color) derived from the ENVISAT data. The data span a time period between 2003-2010. Black dots denote relocated seismicity.

(Lindsey and Fialko, 2013). This suggests a non-negligible contribution of vertical motion. Such a contribution cannot be easily verified by using vertical components of the velocity vectors obtained from GPS data because of the intrinsically larger errors in the GPS-derived vertical component compared to the horizontal components. Also, density of the current GPS network may not be sufficient to capture local deformation.

An efficient way of separating the contributions of vertical and horizontal displacements in the LOS data that involves fewer assumptions and allows one to more fully utilize InSAR measurements is to combine data from different look directions (e.g., Fialko *et al.*, 2001, 2005). Figure 2a shows a horizontal velocity map derived from a combination of InSAR data from the ascending and descending ENVISAT tracks. The data shown in Figure 2a are free of any vertical motion, and are sensitive only to horizontal deformation. Because only two LOS directions were used, we could not independently determine the two orthogonal components of horizontal velocities (e.g., the North and East components), and assumed that the velocity vectors are parallel to the average strike of the San Andreas and San Jacinto faults in the area of interest. As one can see in Figure 2a, the San Felipe Shear Zone is expressed in a high gradient in the surface velocity field (i.e., high strain rate), indicating that the deformation is indeed due to horizontal shear.

To complement and independently verify horizontal velocities obtained from InSAR data in Spring of 2014 we conducted a campaign GPS survey of several monuments in the area of study (Figure 2). These data were combined with results of previous surveys conducted in 2010 and 2011 to obtain secular velocities. Figure 3 shows a comparison of fault-parallel velocities derived from InSAR (black dots) and GPS (red symbols) data. As one can see from Figure 3, the InSAR and

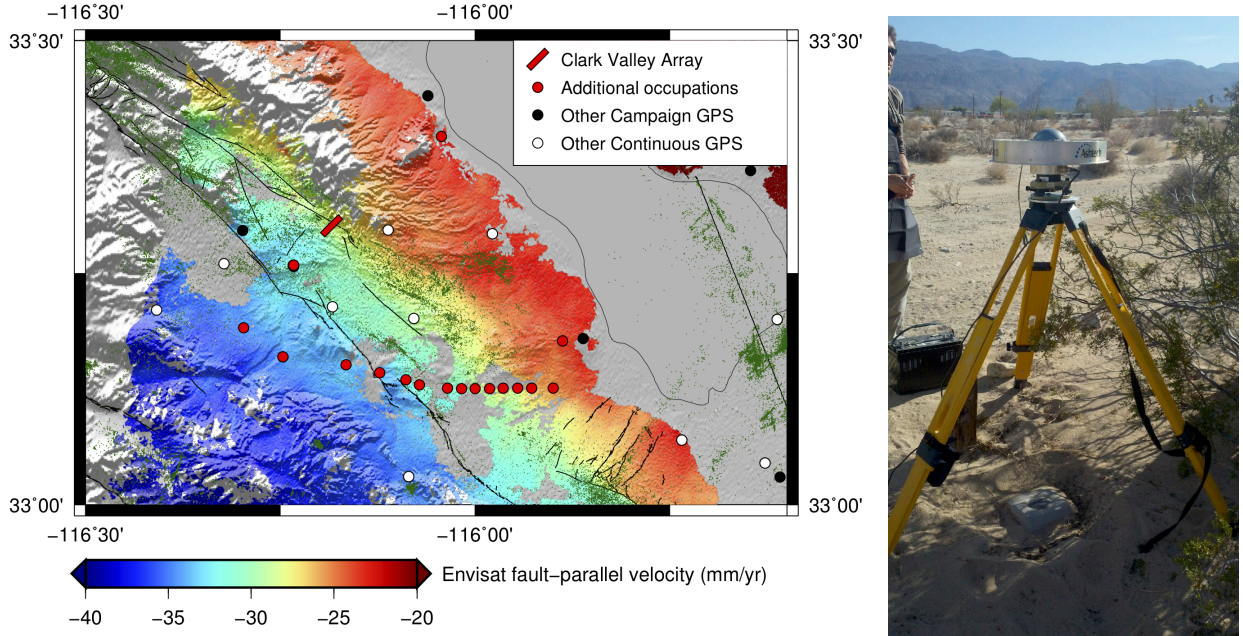


Figure 2: (Left: a) A zoom-in of the horizontal velocities (Figure 1) on the area of study. Red circles denote the campaign GPS sites. Also shown are continuous GPS sites (white circles) and campaign GPS sites for which secular velocities are provided in the CMM4 data set. Colors denote InSAR-derived horizontal velocity field. Green dots denote relocated seismicity. (Right: b) One of the benchmarks of the Hwy 78 array surveyed with campaign GPS.

GPS velocities are in excellent agreement. The high-resolution velocity data confirm asymmetry in the surface strain rate with respect to the Coyote Creek fault, and lend support to the suggested “blind” continuation of the Clark fault. The data also reveal a small (2-3 mm/yr) discontinuity of the velocity profile across the Coyote creek fault, most likely due to shallow creep. An inverse model that accounts for variations in the elastic moduli of the Earth’s crust (*Lindsey and Fialko, 2013*) suggest a slip rate up to 10-12 mm/yr on this unmapped structure. Estimates of the Holocene slip rate on the Coyote Creek segment of the SJF ($\sim 4 - 8$ mm/yr, *Sharp (1967)*) are considerably lower than those on the Clark segment ($\sim 14 - 18$ mm/yr, *Blisniuk et al. (2010)*; *Dorsey (2002)*; *Rockwell et al. (1990)*; *Sharp (1967)*), consistent with the idea that a substantial strain has to be accommodated on some structure to the East of the Coyote Creek fault. Some of this strain can be accommodated by cross-faults such as the Elmore Ranch fault (*Hudnut et al., 1989*). However, the pattern of seismicity and surface deformation (Figure 1) suggest a possibility of localized shear at depth aligned with the trend of the SJF. If so, the inferred “blind” segment of the San Jacinto fault that may be in fact the dominant branch with the average slip rate exceeding that of the sub-parallel Coyote Creek fault. Given an estimated total slip on the San Jacinto fault of the order of many kilometers (*Dorsey, 2002*; *Janecke et al., 2010*; *Sharp, 1967*), the absence of an active fault trace in the inferred shear zone is puzzling. Partly, such an absence might be caused by alluvial burial from the ancient Lake Cahuilla, with the latest high stand as recent as 400 years ago

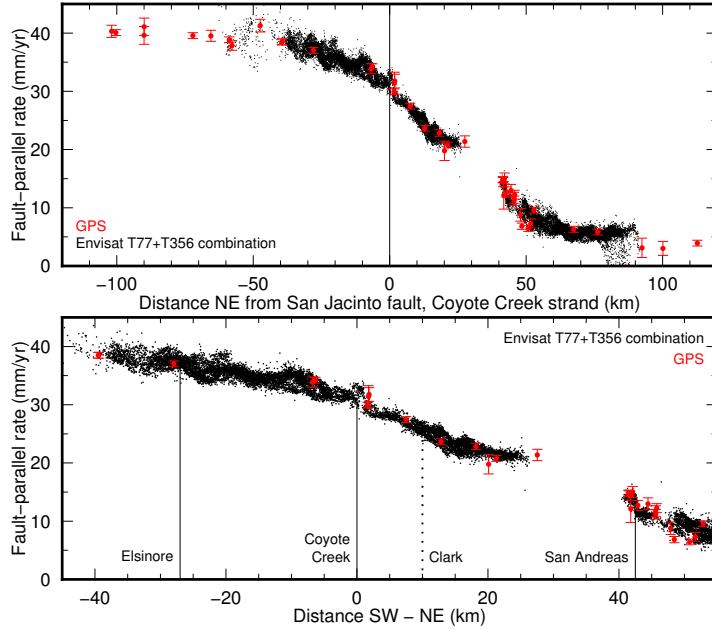


Figure 3: (Top) A velocity profile across the plate boundary faults at latitude of ~ 33 deg. South derived from InSAR (black dots) and GPS (red symbols) data. The profile is centered on the Coyote Creek fault. (Bottom) Zoom-in on the Coyote Creek fault and the San Felipe Shear zone (blind continuation of the Clark fault).

(Waters, 1983). It is also possible that deformation in the uppermost crust comprised of soft lake deposits may be distributed (e.g., Janecke *et al.*, 2010), although other faults in the area that cut through similar rock formations exhibit extremely localized surface slip (e.g., Hudnut *et al.*, 1989; Wei *et al.*, 2009). Our analysis of space geodetic data suggests that the San Felipe Shear Zone is characterized by high deformation rates and may pose a considerable seismic hazard.

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